Telerehabilitation Platform for Hip Surgery Recovery

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***Abstract*—The enhancement of ubiquitous and pervasive computing brings new perspectives in terms of medical rehabilitations. In that sense, the present study proposes a Web-based platform to promote the reeducation of patients after hip replacement surgery. This project focuses on two fundamental aspects in the development of a suitable telerehabilitation application, which are: (i) being based on an affordable technology and (ii) providing the patients with a real-time assessment of the correctness of their movements. A comparative test shows that the movement's evaluation carried out by therapists is consistent with the output of the automatic assessment module. Improvements of the algorithm are discussed, in order to increase the accuracy and depth of the analysis.**

Keywords—telemedicine; motor rehabilitation; motion assessment; natural user interface; Hidden Markov Model

I. Introduction

A current trend in medicine are the remote therapy systems [1, 2]. This concept consists of enabling patients to carry out part of the rehabilitation at home and to communicate through the Internet the evolution of the recovery process. The present study exposes a Web-based platform for physical telerehabilitation for patients after hip arthroplasty surgery. This orthopedic procedure is an excellent case study, because it involves people who need a postoperative functional rehabilitation program to recover strength and joint mobility. However, the condition of these patients makes difficult their transportation to and from the physiotherapist's office. The proposed approach considers two fundamental conditions for the development of a suitable telerehabilitation platform [3]. First, the system must make use of a low-cost motion capture device, in order to be economically viable. Second, the platform should automatically detect the correctness of the executed movement to provide the patient with real-time feedback.

The manuscript is divided into four sections. The first part is a general description of the Web-based platform (frontend and backend). The second part focuses on the assessment module, which automatically classifies the quality of the movement through a Hidden Markov Model approach. The third section consists of a brief presentation of a user-friendly application to enable the therapists to generate assessment models on any kind of new exercises. Finally, some conclusions and perspectives are drawn up regarding the results of the automatic assessment and possible improvements of the algorithm, in order to provides an output that perfectly matches with the analysis carried out by the physiotherapists.

II. Web Platform

A. Global Architecture

One of the main goals of the web application is to be easy to use for patients and physiotherapists. The rehabilitation platform is supported by a client-server architecture (Fig. 1). The server contains the remote application and the associated database. The user's interface enables patients and therapists to manage the display and the use of the Kinect data. The client-server connection is established via WebSocket as communication protocol.

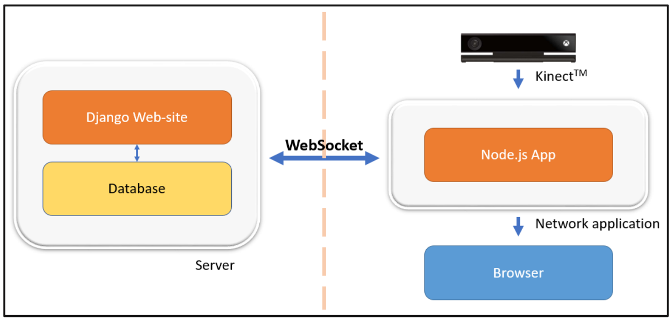

Fig. 1. Platform architecture

1) Django website server: The website is based on Django, a Web framework written in Python. For an effective development, it was decided to use Django CMS, a content managing system which simplifies the implementation of the Web application.

2) Client side: The Kinect camera is used to capture the movements performed by the patient. A network application is launched on the patient's computer, in order to send the data from the Kinect to the Django Website. To perform an exercise and to use the Kinect data, a gateway between the Kinect and the server is necessary to manage the data flow. This application launched in the backend of the system must be able to retrieve the data sent by the Kinect and create a link with the server to send them (Network communication). *Node*.js, a JavaScript run-time environment, is used for this part. It allows the creation of an application coded in JavaScript and HTML; and the communication with the Django server. The backend manages the data from the Kinect and generate an HTML page for the browser. Node.js was chosen for its wide range of modules, and more specifically the library Kinect2 which simplifies the communication with the Kinect. The library http is used to start the application. Fig. 2 shows an example of the JavaScript application created to display the avatar of the patient in a browser. The representation of the avatar (shape and appearance of the joints) can be chosen and the interaction between the patient's hand and the red square at the top of the screen allows the user to start the exercise.

3) WebSocket: Node.js includes a library named Socket.IO and allows the deployment of a real-time bidirectional event-based communication. To do so, the destination address of the data (the address of the server hosting the website) must be declared in the Node.js application, and the IP address of the sender must be declared in the Django Website. Through this method, the library Socket.IO for Python and the one for Node.js are able to communicate by using a function call.

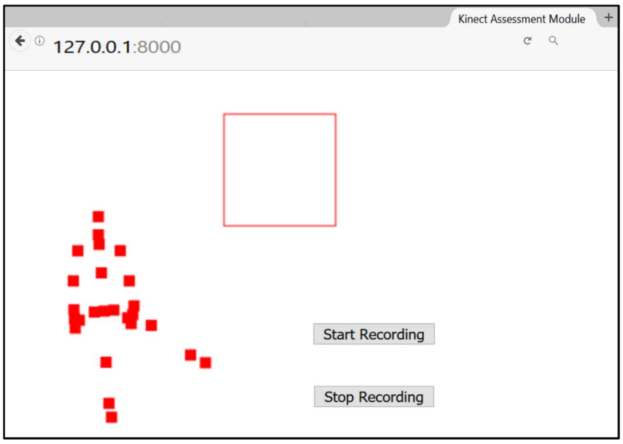

Fig. 2. Patient's interface during the physical rehabilitation protocol

B. User Interfaces

The website can accommodate different types of users, such as a patient or a therapist. The functionalities are singular for these two kinds of users. The rehabilitation is divided into several parts, called stages. Each stage corresponds to a different level in terms of the intensity of: (i) Range of Movement (ROM), (ii) Stretching, (iii) Force, and (iv) Walking. The transition from one stage to another is allowed when the patient complete correctly all the exercises of the current stage and receives the physiotherapist's consent. In other words, the physiotherapist only can unlock a stage according to the progress of the patient.

1) Patient interface: Fig.3 shows the workflow of the patient interface. The patients have the choice to practice exercises, consult their performances, or send a message to the physiotherapist.

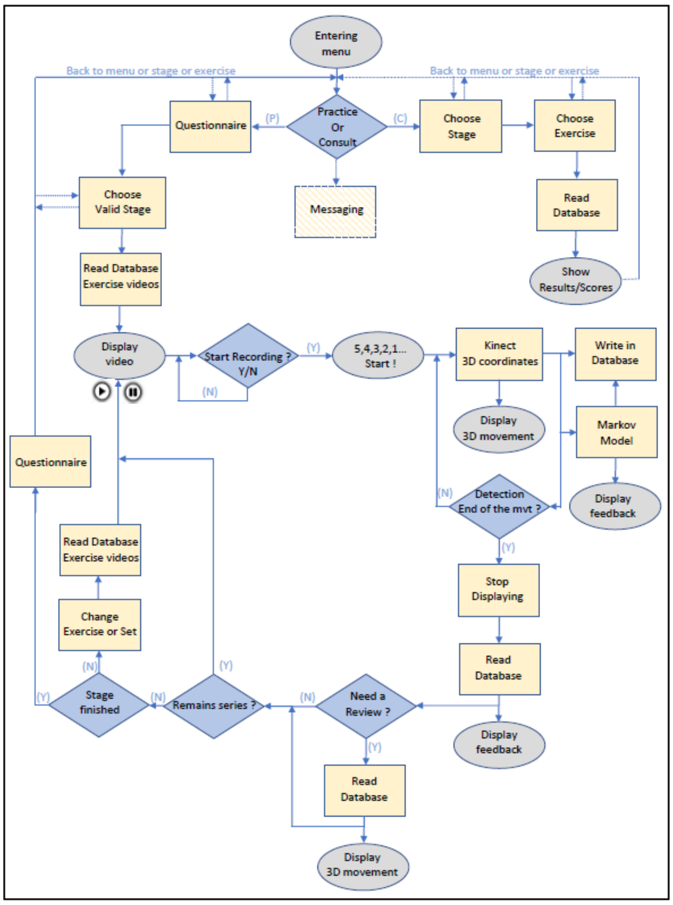

Fig. 3. Workflow of the patient interface

a) Practice: Before the rehabilitation begins, patients must answer a questionnaire, which evaluates their ability to complete the exercises. They must self-assess pain levels, skin problems, and potential edemas. If the questionnaire outputs a low score, the patients are impeded to perform the physical exercises. In the opposite case, the patients can proceed with the rehabilitation protocol. They must choose an available stage and the various associated exercises. The reeducation program is divided into different items. First, they have the option to watch an explanation of the movements. After the exercise is starting, the user's avatar and a real-time feedback on the quality of the movement is displayed on the screen (see, Fig. 2). The 3D joint coordinates received from the Kinect and the assessment associated are saved into the database. At the end of the exercise, the patients can review their movements and have a detailed feedback on their performance. The same questionnaire as previously mentioned is asked to the user at the end of a practical session, in order to provide the therapist with information on the state of the patient after performing the physical exercises.

b) Consult: This section allows the patients to check the results and performances of the exercises they achieved.

c) Messaging: This section allows the patient to exchange messages with the physiotherapist (questions, advice, etc.).

2) Physiotherapist interface: Several functionalities are available for the health professionals. First, they have to create an account if they are not yet registered. After that, as shown in Fig. 4, it is possible to: (i) add a new patient and/or update information on existing patients; (ii) monitor the performance, progress and movements of the patients; and (iii) send and/or receive messages from patients. Physiotherapists have also the possibility to update their personal data.

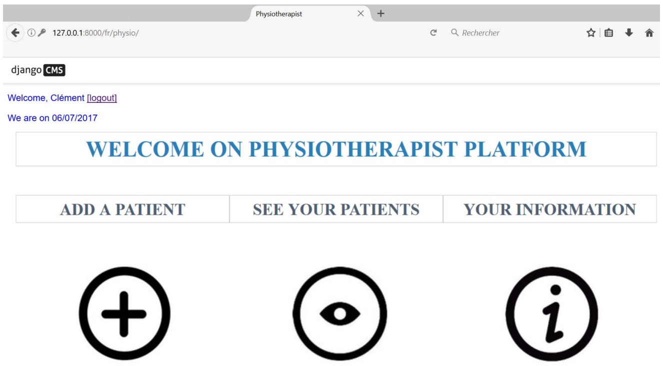

Fig. 4. Physiotherapist interface (main menu)

C. Database Modelling

The database is directly associated with the Django Website. Django CMS integrates a relational database management system named SQLite3, which is adequate for the telerehabilitation platform.

1) User database: This database stores different information about the users, such as: name, e-mail, age, occupation, city, …

2) Exercise database: The modelling of this database is as follows (see, Fig. 5):

a) Main table: This table synthetizes the data about the exercises completed by the patient (date, kind of exercise, stage, completion time, etc.) and the corresponding outcome performance. During the execution of an exercise, fractions of the entire movement are assessed in real-time, in order to evaluate the correctness of the performed movement. Then, a single *outcome* (perfect, good, or bad) is produced based on the sum of these individual assessments (see, next section for more details on the assessment module).

b) Exercises table: This table, linked to the *Main table* through a 1:N relationship, provides details about each exercise and a demo video of the movement that must be performed.

c) Data exercise N° table:* This table, linked to the *Main table* by a 1:N relationship, provides details about the movement performed during an exercise and stores the 3D joint coordinates captured by the Kinect. These data can be used to display a replay of the movement carried out by the patients, in order to provide the physiotherapist with an additional visualization (more ecologic) of the actual performance of the patient.

d) Assessment table: This table is linked to each *Data Exercise N°* table,* through a 1:N relationship, and stores the evaluation calculated by the assessment module for each part of the movement (see Fig.3, Markov Model box).

e) Sets table: This table, linked to the *Main table* by a 1:N relationship, describes the nature of the exercice (balance, coordination, ROM and force).

3) Questionnaire database: This database stores all the questionnaires answered by the patients and provides the physiotherapist with a medical history and a permanent monitoring of the patient's condition.

III. ASSESSMENT MODULE

An automatic assessment of the quality of the performed exercises is implemented according to a Hidden Markov Models (HMM) approach [4]. This technic provides insights in the ontological structure of the rehabilitation exercises and represents a probabilistic interpretation of the correctness of a movement execution [5, 6]. Here, the ontology of different compensatory movements associated with an exercise of hip abduction of the right leg are evaluated from an experiment on healthy participants.

A. Experimental Setup

The representation of the Kinect's skeletal data is based on the degrees of freedom per joints. The created feature vector contains four variables (table I). Two of these features are the absolute value of the linear speeds of the hip center joint and the shoulder center joint (features F0-F1, in table I). The speeds are calculated using a buffer of 15 frames (around 0.25 sec) as a denoising method. The speed is the average of the values contained in the buffer. This buffer gets updated at every frame by discarding the oldest data point and adding the newly one. In this sense the data stream becomes available after the buffer being filled. Also, the angles of the upper legs in frontal planes (feature F3, in table I) are integrated into the model. The angles are calculated with the cosine law. At last, the speed paths of this last feature (feature F2, in table I) is created in the same fashion as stated previously.

TABLE I. FEATURE VECTOR

F0	**F1**
Hip center speed (m/s)	Shoulder center speed (m/s)
F2	**F3**
Right hip speed (θ/s) Frontal plane	Right hip angle (θ) Frontal plane

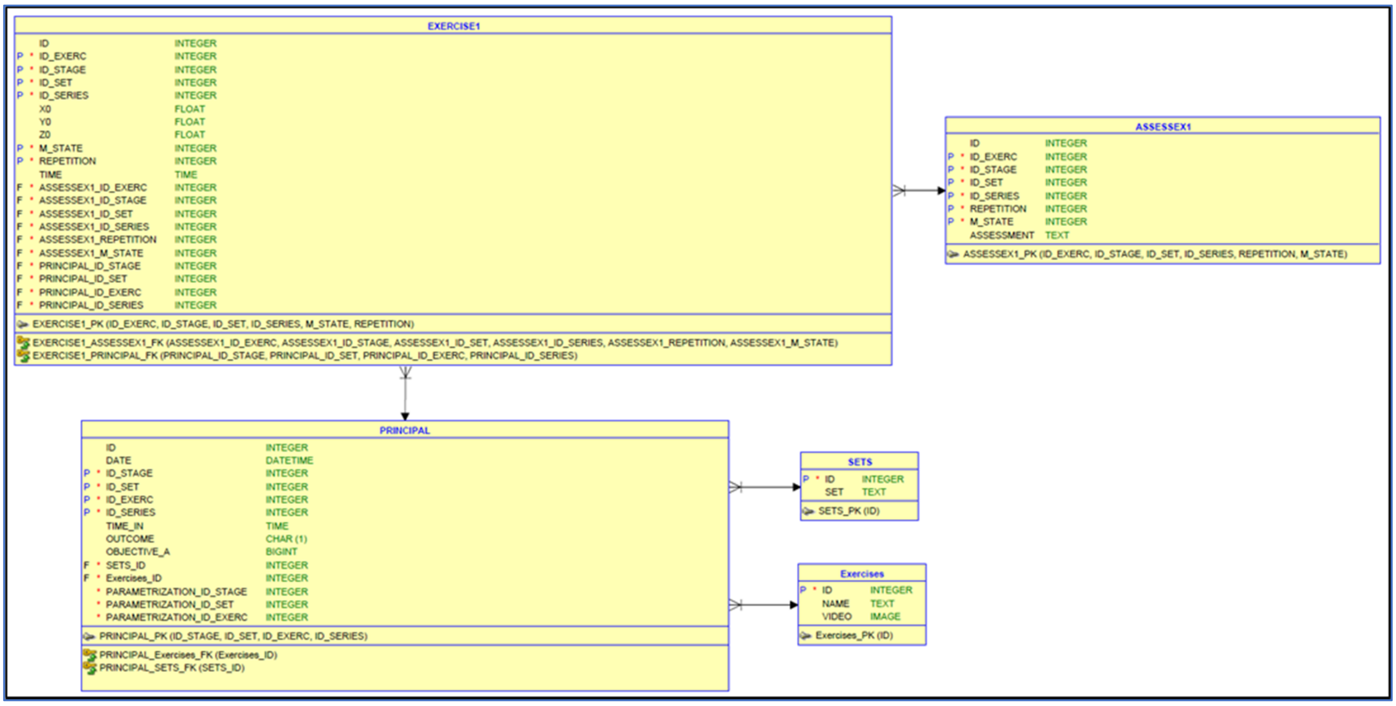

Fig. 5. Architecture of the database

B. *Experimental Protocol*

Nine subjects took part in the study. The experiment consisted of executing a rehabilitation exercise of hip abduction. This exercise was repeated eight times per participant. Simultaneously, five therapists rated the movement on four different aspects. These aspects were range of motion (ROM), coordination, compensation and force. Coordination is related with the synchronicity of different body parts during the execution of an exercise. Compensations were defined as undesired movements, which were not expected to be performed. Subjects received a feedback regarding the correctness of their performance after the fifth repetition. Then, each of the three-remaining repetition was followed by a systematic feedback from the therapists.

C. *Model Training*

HMM is a probabilistic approach that aims to model a given signal into hidden states. These states represent an arbitrary decomposition of the whole movement into successive phases. For instance, the states for hip abduction of the right upper leg are (HMM II, in table II): beginning pose (state 0), moving up (state 1), hold leg up (state 2), and leg down (state 3). Here, two HMMs are independently trained: (i) one on the movement of the trunk (HMM I, in table II); and (ii) another on the movement of the hip in the frontal plane (HMM II, in table II). Table II shows the feature set and the number of states used for training each HMM. The states are used in the next stage to create values to assess synchronicity and symmetry. For a determined individual, HMMs were trained by using the correct data (according to the therapists labelling) of the other eight participants. Thus, a total of eight HMMs per subject was trained. Each model can predict the state of a specific joint or joint group (as the trunk in the skeleton representation is rigid). This is useful as a fault can occur in one of these groups only, while the rest can be correctly executed. In addition, every part of a movement can be correctly executed, but badly synchronized. Such structure enables us to identify if a movement in one joint initialized and stopped earlier or later, as state transitions are easy to obtain. The characteristic pattern of a movement expressed in states leads to the knowledge of which state is associated with the movement initialization and termination.

TABLE II. FEATURE SET AND AMOUNT OF STATES

	HMM I	**HMM II**
Features	0, 1	8, 14
States	3	4
Name	Trunk movement	Right hip frontal

D. *Results*

Here, the performance of three subjects after the execution of a movement of hip abduction are presented. The result of the labelling shows a global consensus, but also some inconsistences between the therapists. Table III shows the labels for this sample of three participants. For each colorized horizontal strip, the first row is the ROM rating, the second row is the coordination rating, the third row is the compensation level, and the fourth row is the force rating.

The compensation is estimated through the symmetry of the movement, because it provides us with an insight on the motor control over the execution, which must be characterized by an evenly distribution of the agonist and antagonist muscular load in case of symmetry. It is first calculated by extracting the signal of the shoulder center joint on both terminations: beginning and end of the rest state (0).

TABLE III. LABELS FOR A SAMPLE OF THREE SUBJECTS (ONE DIFFERENT COLOUR FOR EACH SUBJECT). THE DIGITS CORRESPOND TO THE ID NUMBER OF THE TRIAL.

	Therapist 1			Therapist 2			Therapist 3			Therapist 4			Therapist 5		
	excellent	good	bad	excellent	good	bad	excellent	good	bad	excellent	good	bad	excellent	good	bad
ROM	12345678			12345678			12345678			12345678			12345678		
Coordination	12345678			12345678			12345678			12345678			12345678		
Compensation	12345678			12345678			12345678			12345678			12345678		
Force	12345678			12345678			12345678			12345678			12345678		
ROM	12345678			12345678			12345678			12345678			12345678		
Coordination	1234568	7		158	23467		1234578	6		3468	1257		12345678		
Compensation	134578	26		12345678	4		234568	17		34578	126		23468	157	
Force	12345678			12345678			12345678			12345678			12345678		
ROM	12345678			12345678			12345678			2345678	1		12345678		
Coordination	12345678			134578	26		12345678			2468	1357		1245678	3	
Compensation	1345678	2		1345678	2		2678	1345		2468	1357		23478	156	
Force	12345678			12345678			12345678			12345678			12345678		

As shown in figures 6A and 6B, this processing provides a middle area (shown in green, HMM I) where the minimum value corresponds to the center of the total movement of the shoulder center. Then, the symmetry is expressed in differences in length (or number of frames) between the left and right side in relation to this minimum value. A ratio is obtained by dividing the time took to reach the maximum amplitude where speed ≈ 0 (inversion of the direction of the movement represented by the green valley in figures 6A and 6B) and the time took to return to the initial pose (end of the movement). Columns 5 to 7 of table IV show these ratios. Values >1 mean that returning to the initial pose took longer than reaching the maximum amplitude of the movement and inversely for ratios <1.

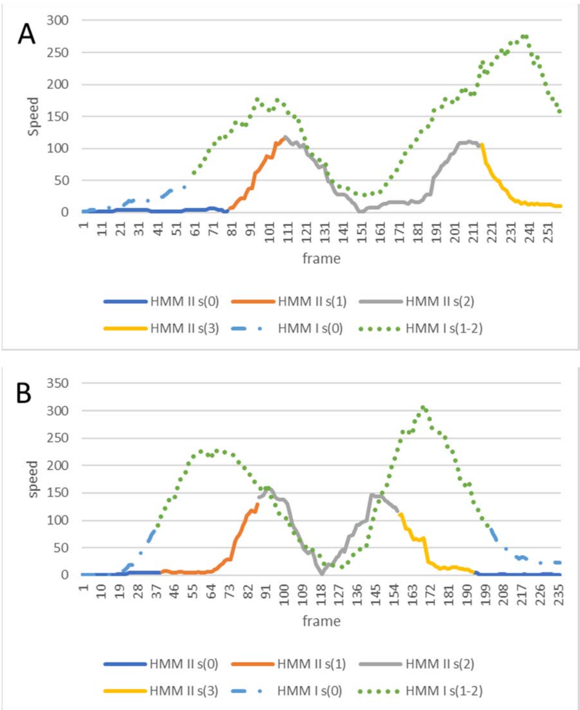

Fig. 6. Speed path of the shoulder center (dotted lines) and angular speed of the right hip (continuous lines), for two different trials of an exercise of hip abduction: trial 7 of subject 2 (A) and trial 2 of subject 1 (B). The linear speed of the shoulder center is 1500 times magnified in this representation. The x-axis represents the number of frames, where every frame has a period of time of 1/60 sec. The y-axis represents the velocity in m/s for the shoulder movement and θ/s for the hip movement.

The coordination is calculated by using the target movement (HMM II) and the relative shift in time of the movement of the trunk (HMM I). The shift in time is calculated by taking the midpoint of the sequenced state 2 (where maximum amplitude is reached) of HMM II and the relative difference in lengths of the shoulders clipping points on the left and the right side of this point. Figures 6A and 6B show an example of an incorrect vs. correct coordination of the movements, respectively. Figure 6A corresponds to the trial 7 of subject 2, which was classified by three therapists as not perfectly coordinated (see, blue strip in table III). It can be noted on this trial a minor shift of the speed paths of the shoulder center to the left with respect to the angular speed of the hip abduction (ratio = 0.72, which is lower than the average value of 0.8 for this individual). In contrast, Figure 6B shows a trial that is almost perfectly synchronized (ratio = 0.94) as both valleys (movement of shoulder center and movement of abduction) are close to align.

TABLE IV. SYNCHRONICITY BETWEEN SHOULDER MOVEMENT AND SYMMETRY OF SHOULDER MOVEMENT. VALUES CLOSE TO 1 RESEMBLE A PERFECT SYNCHRONICITY OR SYMMETRY. FOR SYNCHRONICITY, VALUES <1 MEAN THAT THE SHOULDERS MOVED BEFORE THE HIP ABDUCTION AND VALUES >1 MEAN THAT THE SHOULDER CENTER MOVED AFTER THE HIP ABDUCTION. FOR SYMMETRY, SCORES <1 MEANS THE SHOULDER CENTER REACHED THE MAXIMUM AMPLITUDE FASTER THAN IT RETURNED TO THE BEGINNING POSE AND THE OPPOSITE FOR SCORES >1. FOR VALUES >1 AN INVERSE VALUE (1/VALUE) IS GIVEN IN PARENTHESIS IN ORDER TO CALCULATE THE AVERAGE VALUE FOR SYNCHRONICITY AND SYMMETRY.

	Subject 1 synchronicity	**Subject 2 synchronicity**	**Subject 3 synchronicity**
Trial 1	0.93	0.79	0.95
Trial 2	1.06 (0.94)	1.16 (0.86)	0.74
Trial 3	0.86	0.91	1.21 (0.82)
Trial 4	0.73	0.61	0.64
Trial 5	1.54 (0.65)	0.74	0.73
Trial 6	0.93	0.93	0.71
Trial 7	0.74	0.72	2.14 (0.46)
Trial 8	1.01 (0.99)	0.84	0.87
AVERAGE	**0.85**	**0.8**	**0.74**

	Subject 1 symmetry	Subject 2 symmetry	Subject 3 symmetry
Trial 1	1.09 (0.92)	0.79	0.95
Trial 2	1.29 (0.78)	1.0	0.94
Trial 3	0.82	0.93	1.4 (0.71)
Trial 4	0.85	0.60	0.87
Trial 5	1.54 (0.65)	0.78	0.82
Trial 6	1.01 (0.99)	0.83	0.76
Trial 7	0.78	0.68	3.4 (0.29)
Trial 8	1.16 (0.86)	0.76	1.0
AVERAGE	**0.83**	**0.79**	**0.79**

IV. HMM TRAINING APPLICATION

An application was created to enable the therapists to easily create new assessment models that could be applied on any kind of rehabilitation exercises. CSV files can be loaded by clicking an HMM button. Before doing so, the features that are going to be used in training need to be assigned by typing them in the features section. To analyze the optimal amount of states that a dataset requires, Bayesian Information Criteria (BIC) can be performed. This creates a score using cross validation for states 2-10 (as a HMM exists at least out of 2 states). The amount of states to be used during the training can be declared in the states section. When all the parameters are set, the training button appears and the training can take place. When this step is done, the models can be saved. An example of the user interface of the application is shown in figure 7.

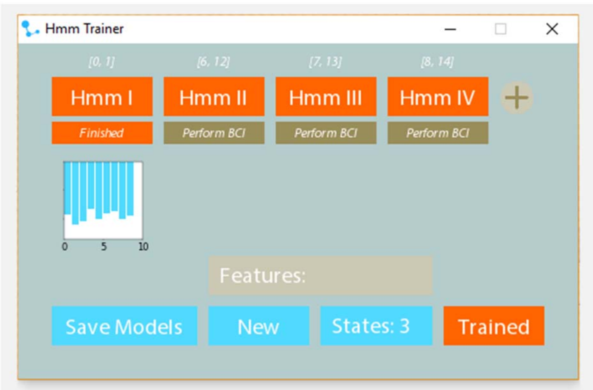

Fig. 7. User graphic interface of the HMM trainer

V. CONCLUSIONS AND PERSPECTIVES

The assessment module seems to capture to some extend the levels of synchronicity and compensation perceived by the therapists. However, the algorithm could be substantially improved by including the total displacement of the trunk during the movement and a symmetric value for the distribution of the displacement, in which the total displacement would aid in detecting the allowed movements (not considered as compensation) and symmetry in displacement would provide an insight regarding the smoothness of the movements. In addition, the precision of the synchronicity could be increased by applying a curve fitting to the middle section of the speed paths (for shoulder and hip) and calculating the shift between the minimum of each curve. Also, more information on the compensatory movements could be obtain by determining the movement of the subjects regarding both the sagittal and the frontal planes. Finally, the algorithm could be adapted to a Hidden Semi-Markov Models (HSMMs), in which the sequences are modelled in terms of duration distributions [7]. This approach allows for a higher flexibility of the transition probability than in the HMMs, which should increase the classification accuracy [8].

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